Report on the Bilateral Comparison between DPLA-DFM and NPLI

Summary

The DPLA-DFM (Denmark) and the NPLI (India) have carried out a bilateral comparison as an extension of the CCAUV.A-K3 Key Comparison organized by the CCAUV. The DPLA-DFM undertook the role of the Pilot laboratory. The measurements took place immediately after the measurements of the CCAUV.A-K3 Comparison. Two of the LS2aP microphones used in that comparison were used in the bilateral comparison before the results were announced. This report includes the measurement results from the participants, information about their calibration methods, and the analysis leading to the assignation of degrees of equivalence and the link to the CCAUV.A-K3.

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Content

1 Introduction

The CCAUV.A-K3 comparison under the auspices of the CCAUV-BIPM was underway between 2003 and 2006. NPLI was one of the original participating NMIs. However, it was not possible for NPLI to follow the planned schedule, and thus NPLI had to abandon the participation in the main Comparison. It was agreed that a bilateral comparison between DPLA-DFM and NPLI should take place immediately after the termination of the measurement round of the Comparison CCAUV.A-K3. Thus, this comparison is a bilateral comparison that supplements the CCAUV.A-K3 key comparison organised by the CCAUV.

It was also agreed that the protocol of the CCAUV.A-K3 comparison should be followed, the only deviation being that the microphones were transported by a courier company (DHL) rather than by hand. The standards to be calibrated were two LS2aP microphones already used for the CCAUV.A-K3 key comparison. The calibration technique was restricted to be the reciprocity technique in the frequency range from 31.5 Hz to 4 kHz in octave intervals and from 6.3 kHz to 25 kHz in 1/3-octave intervals. The measurements took place between October 2003 and January 2004. Control measurements at DPLA-DFM were performed before the microphones were sent to NPLI, and after NPLI finished its measurements.

This report includes the measurement results from the participants, information about their calibration methods, and the analysis leading to the assignation of equivalence degrees and the link to the CCAUV.A-K3. The reader is referred to the protocol and reports of the CCAUV.A-K3 for further information about the measurement requirements, frequencies of interest, methods used in the treatment of the data, etc.

2 Comparison protocol

The protocol followed in the comparison is based on the CCAUV.A-K3 protocol. However, like two of the participants in the CCAUV.A-K3 comparison NPLI performed the measurements at exact frequencies. The results from NPLI has been corrected to nominal frequencies using the same method as outlined in the CCAUV.A-K3 report. The microphones were transported by a courier company (DHL). The container used under the courier transportation was provided by DPLA-DFM.

3 Travelling microphones

Two LS2 microphones, Brüel & Kjær 4180, serial numbers 1124046 and 1395455, were supplied by DPLA-DFM. The microphones are the same as used in circulation B in the preceeding CCAUV.A-K3 key comparison. Figure 1 shows DPLA-DFM’s results of the control calibrations for some selected frequencies during the comparison span. The results over the whole frequency range of the two microphones are also shown.

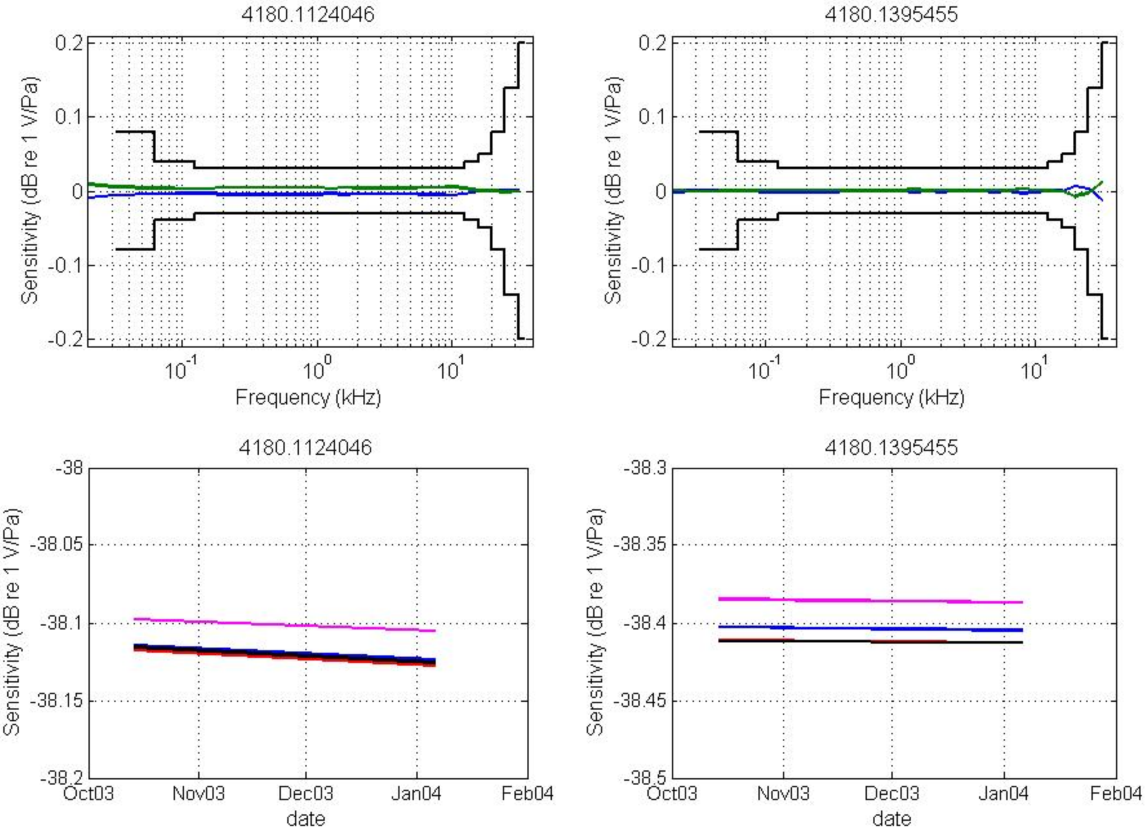

Figure 1. Upper charts: DPLA-DFM measurements as a function of frequency, with the DPLA-DFM uncertainty bounds. Lower charts: Time history of the calibrations performed at DPLA-DFM during the comparison. Blue line: 250 Hz; red line 500 Hz; black line 1 kHz; and magenta line 2 kHz.

4 Results

4.1 Calibration methods

A description of the calibration methods and the reporting of results of each laboratory is given below. The description of the method used in DPLA-DFM is taken from the '*Final Report on the Key Comparison CCAUV.A-K3*' (Ref. [CCAUV.A-K3]).

DPLA-DFM:
"DPLA-DFM measured the standards at least once before and after being sent to every other laboratory. The very first measurement round for each microphone reported by DPLA-DFM has been used as the officially reported DPLA-DFM result.
<u>Measurement principle</u>
The calibration is performed as a full reciprocity calibration according to IEC 61094 2, using three microphones pair wise coupled through air filled Plane Wave couplers of different lengths (nominal lengths 3-4-5-6 mm). The resulting sensitivity is calculated using the MP.EXE software. Radial wave motion correction is applied.
<u>Measuring equipment</u>
The main component of the equipment used is a calibration apparatus developed and built in 1984 at DTU. The receiver microphone is connected to a preamplifier B&K 2673 with insert voltage facilities (driven ground shield) and the current through the transmitter microphone is determined by the voltage across an impedance in series with the microphone. This measurement impedance (nominal 10nF || 0.7MOhm) is calibrated in the frequency range 60 Hz to 40 kHz and the results extrapolated down to 20 Hz. An external polarization voltage was applied by a Fluke DC Voltage Calibrator type 343A. The static pressure is measured by a calibrated barometer, Druck DPI 140 and the temperature by a Pt 100 resistance located close to the coupler. All measurements are conducted in a temperature controlled room at 23.0ºC ± 1.5ºC. Humidity is kept within the range 40% - 60% RH.
The transfer function is measured using a two channel B&K Pulse analyzer in connection with SSR software (Steady State Response software). The measurements were conducted in 1/12 octave steps from 20 Hz to 31.5 kHz. Each transfer function is determined as the average of 5 sweeps with a detector band of 0.01 dB.
The microphone front cavity depth is measured using a depth focussing microscope.
The remaining microphone parameters are determined by data fitting of the results obtained using the above mentioned 4 couplers. Once determined the microphone parameters remain unchanged during all calibrations. Due to longitudinal resonances in the couplers the high frequency limits for the couplers are 35, 32, 24 and 21 kHz resp. Thus, at the highest frequencies the results are the average of a calibration in only two couplers."

NPLI:
"The condenser microphones were calibrated by absolute method on the Reciprocity Calibration System (B&K Type 9699) in the frequency range 31.5 Hz to 25.0 kHz using plane wave couplers. Using three standard microphones in successive pairs the open-circuit voltage sensitivities of the microphones were obtained by using a combination of reciprocity calibration and insert voltage technique. The microphones were acoustically coupled in pairs by the air enclosed in a coupler. For each pair, one microphone was used as a sound source (Transmitter) and the other as a receiver. The task was to measure the electrical transfer impedance UR/ iT where UR is the open circuit voltage of the receiver microphone and iT is the current through the transmitter microphone. The current through the transmitter microphone was found by measuring the voltage across a reference capacitor connected in series with the microphone. The measurements were controlled

by PC software running on the Windows platform. For each frequency three sets of measurements were made and the measurement data were stored in a text file along with microphone identification and ambient parameters. Using these information the calculation programme calculates the sensitivities of the three microphones in accordance with IEC-61094-2. Also the sensitivities valid at reference ambient conditions (Room Temperature T = 23 °C, Static Pressure Ps = 101.325 kPa and Relative Humidity RH = 50%) were calculated through the use of built-in microphone correction data. To increase the accuracy repeated calibrations were made using different couplers, thus allowing the determination of the total volume along with other microphone parameters by an iterative process giving convergent results. "

4.2 Microphone parameters

The values of the microphone parameters have been reported as the equivalent volume, v_{eq}, resonance frequency, f_0, and loss factor, d.

The values of the microphone parameters reported by each laboratory are given in table 1.

Table 1. Acoustic parameters of the microphones

	4180.1124046		4180.1395455	
	DPLA-DFM	NPLI	DPLA-DFM	NPLI
Front volume (mm3)	32.6	34.2	33.0	35.1
Equivalent volume (mm3)	9.2	9.24	9.6	9.14
Loss factor	1.1	1.05	1.03	1.05
Resonance frequency (kHz)	23.5	24.8	21.8	24.8
Front cavity depth (mm)	0.481	0.50	0.488	0.51
Temp. coeff. at 250 Hz (dB/K)	-0.0031	-0.0012	-0.0015	-0.0012
Static press. coeff. At 250 Hz (dB/kPa)	-0.00577	-0.0055	-0.0057	-0.0055

4.3 Microphone sensitivities

The microphone sensitivity reported by each laboratory for each microphone is given in tables 2a and 2b below. The sensitivity is given in dB re 1 V/Pa. The expanded uncertainty corresponding to a confidence interval of 95.6 % is also shown in tables 2a and 2b. NPLI reported the sensitivity at exact frequencies (as shown in table 2a); therefore, an interpolation procedure identical to the one used in the CCAUV.A-K3 report was applied in order to obtain the sensitivity at nominal frequencies (shown in table 2b).

Table 2a - Sensitivity in dB re 1V/Pa of the microphones at exact frequencies, and the expanded uncertainty (k = 2) in dB declared by NPLI.

Frequency	4180.1124046	4180.1395455	Uncertainties
31.60	-38.07	-38.33	0.10
63.10	-38.08	-38.35	0.10
125.89	-38.09	-38.37	0.10
251.19	-38.10	-38.38	0.10
501.19	-38.11	-38.39	0.10
1000.00	-38.11	-38.40	0.10
1995.26	-38.09	-38.37	0.10
3981.07	-38.00	-38.25	0.10
6309.57	-37.84	-38.02	0.10
7943.28	-37.69	-37.81	0.10
10000.00	-37.56	-37.59	0.10
12589.30	-37.47	-37.41	0.10
15848.90	-37.79	-37.73	0.10
19952.60	-38.99	-39.22	0.10
25118.90	-41.30	-41.95	0.14

Table 2b - Sensitivity in dB re 1V/Pa of the microphones at nominal frequencies, and the expanded uncertainty (k = 2) in dB declared by the laboratories.

	4180.1124046		4180.1395455		Uncertainties	
Frequency	DPLA-DFM	NPLI	DPLA-DFM	NPLI	DPLA-DFM	NPLI
31.5	-38.069	-38.070	-38.350	-38.330	0.08	0.10
63	-38.091	-38.080	-38.372	-38.350	0.04	0.10
125	-38.105	-38.090	-38.389	-38.370	0.03	0.10
250	-38.114	-38.100	-38.403	-38.380	0.03	0.10
500	-38.118	-38.110	-38.411	-38.390	0.03	0.10
1000	-38.116	-38.110	-38.412	-38.400	0.03	0.10
2000	-38.098	-38.090	-38.385	-38.370	0.03	0.10
4000	-38.011	-38.001	-38.264	-38.251	0.03	0.10
6300	-37.852	-37.839	-38.038	-38.019	0.03	0.10
8000	-37.721	-37.694	-37.836	-37.817	0.03	0.10
10000	-37.579	-37.560	-37.613	-37.590	0.03	0.10
12500	-37.512	-37.471	-37.452	-37.409	0.04	0.10
16000	-37.845	-37.762	-37.781	-37.697	0.05	0.10
20000	-39.005	-38.972	-39.199	-39.198	0.08	0.10
25000	-41.216	-41.355	-41.741	-42.009	0.14	0.14
31500	-43.914		-44.478		0.20	

5 Analysis of the results

The nature of this comparison —2 participants following a single loop with two travelling standards— should make it possible to use simple methods for estimating the comparison reference value such as those used in the comparison CCAUV.A-K1. However, the comparison has to be linked to the CCAUV.A-K3. A flexible approach based on least-squares approximation [Nielsen2002] was used for linking of the results to the Key Comparison.

In general a linear model described by $\mathbf{E}(\mathbf{y}) = \mathbf{X} \cdot \mathbf{a}$ has to be solved for each frequency. In the model **a** is a vector of parameters of the model, **E**(**y**) is the expectation of the measurements and **X** is the design matrix [Nielsen2002]; these values are the values that should have been measured in absence of uncertainty. The vector **y** is conformed by the *n* measurement values provided by the participants on at least one of the circulated measurement objects. The elements of the design matrix are known a priori with zero uncertainty. The parameters $a_1 \ldots a_k$, $k \geq 1$, are unknown and have to be estimated from the *n* measurement results provided by the participants **y**, and the associated covariance matrix Σ.

The covariance matrix Σ is the sum of two matrixes: Σ_{meas}, which contains the square of the uncertainties claimed by the participants (diagonal elements) and the covariances between the provided measurement results (off-diagonal elements), and Σ_{object}, which contains only diagonal elements that describe the estimated variance of the value of the measurand due to random instability of the circulated objects. Once these matrices have been built, the unknown parameters in the model and the reference values of the comparison can be estimated following the rest of the procedure described in reference [Nielsen2002].

If the reference values of this particular comparison were to be estimated, the design matrix, the covariance matrix and the matrix of the results of the participants should only be constructed using data from this comparison. However, in order that this comparison can be linked to the CCAUV.A-K3 comparison, the matrices are built using data from the CCAUV.A-K3 comparison and the Bilateral Comparison as if it was a single comparison. As the reference values from the Key Comparison must not change, the participants in the Bilateral Comparison, except DPLA-DFM that will serve as a link, are excluded from the determination of the reference value. The model looks then like

$$
\begin{bmatrix} E(y_{11}) \\ \vdots \\ E(y_{19}) \\ E(y_{21}) \\ \vdots \\ E(y_{29}) \\ E(y_{31}) \\ \vdots \\ E(y_{38}) \\ E(y_{41}) \\ \vdots \\ E(y_{48}) \\ E(y_{51}) \\ E(y_{52}) \\ E(y_{61}) \\ E(y_{62}) \end{bmatrix}
=
\begin{bmatrix}
1 & 0 & 0 & 0 & & \\
\vdots & \vdots & \vdots & \vdots & & \\
1 & 0 & 0 & 0 & & \\
0 & 1 & 0 & 0 & & \\
\vdots & \vdots & \vdots & \vdots & & \\
0 & 1 & 0 & 0 & \multicolumn{2}{c}{0} \\
0 & 0 & 1 & 0 & & \\
\vdots & \vdots & \vdots & \vdots & & \\
0 & 0 & 1 & 0 & & \\
0 & 0 & 0 & 1 & & \\
\vdots & \vdots & \vdots & \vdots & & \\
0 & 0 & 0 & 1 & & \\
 & & & & 1 & 0 \\
 & & & & 1 & 0 \\
 & \multicolumn{2}{c}{0} & & 0 & 1 \\
 & & & & 0 & 1
\end{bmatrix}
\cdot
\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{bmatrix},
\qquad (1)
$$

where $E(y_{ij})$ is the expected value of the i-th standard being measured in the j-th laboratory in the loop. The elements of the vector a_j are the parameters to be estimated for the standard i. The standards i = 1… 4 are from the CCAUV.A-K3 comparison. The standards i = 5, 6 are the microphones circulated in the Bilateral Comparison.

The covariance matrix is a 38x38 matrix that contains the declared uncertainties from each laboratory in the two comparisons. As well as in the case of the CCAUV-A.K3, the correlation value for measurements carried in the same laboratory is set to 0,7. Once these matrices are complete, the estimates of the unknown parameters of the model can be calculated using:

$$
\begin{aligned}
\hat{\mathbf{a}} &= \mathbf{C}\mathbf{X}_r^T\boldsymbol{\Sigma}_r^{-1}\mathbf{y}_r, \\
\mathbf{C} &= \left(\mathbf{X}_r^T\boldsymbol{\Sigma}_r^{-1}\mathbf{X}_r^T\right)^{-1}.
\end{aligned}
\qquad (2)
$$

where $\mathbf{y}_r$ and $\mathbf{X}_r$ are obtained from $\mathbf{y}$ and $\mathbf{X}$ given in (1) by deleting the rows associated with the laboratories excluded from the calculation of the reference values, and $\boldsymbol{\Sigma}_r$ is the covariance matrix associated with the reduced data set $\mathbf{y}_r$

The reference values of the comparison and the associated covariance matrix should be calculated using:

$$
\begin{aligned}
\hat{\mathbf{y}} &= \mathbf{X}\hat{\mathbf{a}}, \\
V(\hat{\mathbf{y}}) &= \mathbf{X}V(\hat{\mathbf{a}})\mathbf{X}^T.
\end{aligned}
\qquad (3)
$$

The degrees of equivalence are obtained using:

$$
\begin{aligned}
\mathbf{D}_{\mathbf{ii}} &= \mathbf{A}^T(\mathbf{y}-\hat{\mathbf{y}}), \\
V(\mathbf{D}_{\mathbf{ii}}) &= \mathbf{A}^T V(\mathbf{y}-\hat{\mathbf{y}})\mathbf{A},
\end{aligned}
\qquad (4)
$$

where $\mathbf{D_{ii}}$ is the degrees of equivalence per laboratory, **A** is an averaging matrix. The inter-laboratory degrees of equivalence can be estimated using [CCAUV.A-K3]:

$$D_{ij} = D_{ii} - D_{jj}, \quad V\left(D_{ij}\right) = u_{ii} + u_{jj} - u_{ij} - u_{ji}, \qquad (5)$$

where D_{ij} is the inter-laboratory deviation. The u_{xx} elements are obtained from equation (4).

The consistency of results was tested using the procedure described in [Nielsen2002].

6 Results

6.1 Reference values

As well as in the case of the CCAUV.A-K3 comparison, there is not a single key comparison reference value, but one per frequency associated with each one of the standards circulated. The reference values are listed below in table 3. These values were obtained using the procedure described in the previous section (equation (3)).

Table 3. Reference values for the comparison.
Sensitivities M_p in dB re 1V/Pa and expanded uncertainty u (k = 2) in dB.

Freq. (Hz)	4180.1124046		4180.1395455	
	M_p	u $k=2$	M_p	u $k=2$
31.5	-38.065	0.051	-38.346	0.051
63	-38.089	0.026	-38.370	0.026
125	-38.102	0.020	-38.387	0.020
250	-38.111	0.020	-38.399	0.020
500	-38.114	0.020	-38.408	0.020
1000	-38.112	0.020	-38.408	0.020
2000	-38.094	0.020	-38.382	0.020
4000	-38.008	0.020	-38.261	0.020
6300	-37.852	0.020	-38.038	0.020
8000	-37.719	0.021	-37.834	0.021
10000	-37.577	0.022	-37.610	0.022
12500	-37.513	0.028	-37.452	0.028
16000	-37.854	0.035	-37.790	0.035
20000	-39.018	0.054	-39.213	0.054
25000	-41.214	0.093	-41.739	0.093
31500	-44.070	0.161	-44.634	0.161

6.2 Degrees of equivalence per laboratory

The degrees of equivalence per laboratory were determined as mentioned in the previous section (equation (4)). Figure 2 and table 4 show deviations and the degrees of equivalence per laboratory as a function of frequency.

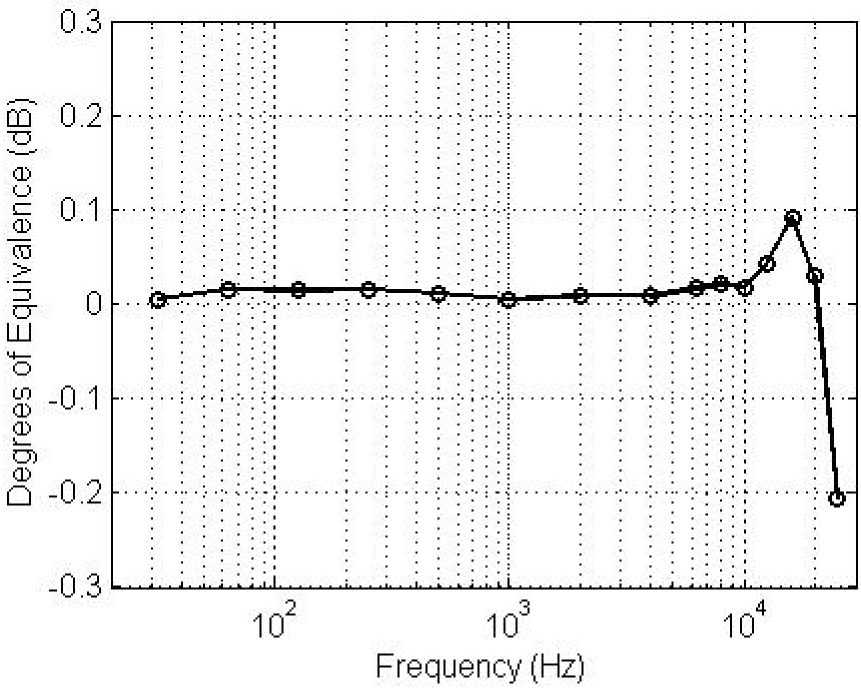

Figure 2. NPLI's deviations in dB as a function of frequency

Table 4 Degrees of equivalence per laboratory as a function of frequency: deviations (dB) and uncertainties *k*=2 (dB)

	Deviations		Uncertainty	
Frequency (Hz)	DPLA-DFM	NPLI	DPLA-DFM	NPLI
31.5	-0.005	0.005	0.069	0.081
63	-0.002	0.015	0.033	0.074
125	-0.003	0.014	0.024	0.073
250	-0.004	0.015	0.025	0.073
500	-0.004	0.011	0.025	0.073
1000	-0.004	0.005	0.025	0.073
2000	-0.003	0.008	0.025	0.073
4000	-0.003	0.008	0.025	0.073
6300	0.001	0.016	0.024	0.073
8000	-0.002	0.021	0.024	0.073
10000	-0.003	0.018	0.023	0.073
12500	0.000	0.042	0.031	0.075
16000	0.010	0.092	0.040	0.076
20000	0.015	0.030	0.065	0.084
25000	-0.002	-0.206	0.116	0.125
31500	0.172		0.132	

6.3 Degrees of equivalence and link to CCAUV.A-K3

Figure 3 and tables 5 and 6 contain the inter-laboratory degrees of equivalence of this comparison linked to the CCAUV.A-K3 Key Comparison. Although the degrees of equivalence are presented for two frequencies, 250 Hz and 1000 Hz, the degrees of equivalence at 1 kHz are selected as reference for this comparison.

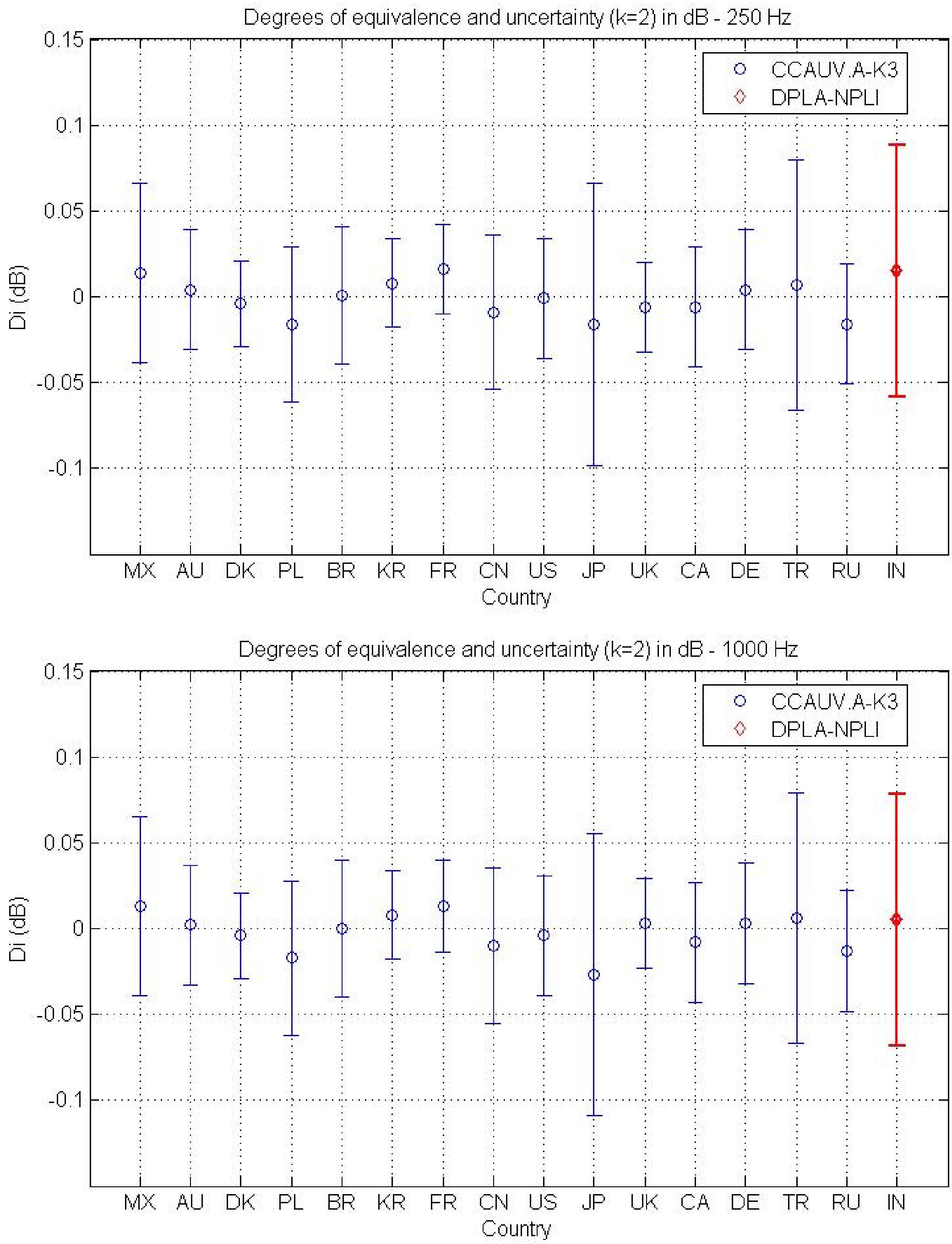

Figure 3 – Inter-laboratory degrees of equivalence in dB at 250 Hz and 1000 Hz linked to the CCAUV.A-K3 key comparison

Table 5 - Inter-laboratory degrees of equivalence at 250 Hz
The upper triangle contains the differences (dB); the lower triangle contains the uncertainties *k* =2 (dB)

250 Hz	CENAM	DPLA-DFM	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB	CSIRO	INMETRO	NIM	NRC	UME	VNIIFTRI	NPLI
CENAM	-	0.018	0.030	0.006	-0.002	0.015	0.030	0.020	0.010	0.010	0.013	0.023	0.020	0.007	0.030	-0.001
DPLA-DFM	0.059	-	0.012	-0.012	-0.020	-0.003	0.012	0.002	-0.008	-0.008	-0.005	0.005	0.002	-0.011	0.012	-0.019
GUM	0.070	0.053	-	-0.024	-0.032	-0.015	0.000	-0.010	-0.020	-0.020	-0.017	-0.007	-0.010	-0.023	0.000	-0.031
KRISS	0.059	0.038	0.054	-	-0.008	0.009	0.024	0.015	0.005	0.004	0.008	0.017	0.014	0.002	0.024	-0.007
LNE	0.059	0.038	0.054	0.039	-	0.017	0.032	0.022	0.012	0.012	0.015	0.025	0.022	0.009	0.032	0.001
NIST	0.064	0.045	0.059	0.046	0.046	-	0.015	0.006	-0.005	-0.005	-0.001	0.008	0.005	-0.007	0.015	-0.016
NMIJ	0.098	0.087	0.095	0.087	0.087	0.091	-	-0.010	-0.020	-0.020	-0.017	-0.007	-0.010	-0.023	0.000	-0.031
NPL	0.059	0.038	0.054	0.039	0.039	0.046	0.087	-	-0.010	-0.010	-0.007	0.003	0.000	-0.013	0.010	-0.021
PTB	0.064	0.045	0.059	0.046	0.046	0.052	0.091	0.046	-	0.000	0.003	0.013	0.010	-0.003	0.020	-0.011
CSIRO	0.064	0.045	0.058	0.044	0.044	0.051	0.090	0.044	0.051	-	0.004	0.013	0.010	-0.003	0.020	-0.011
INMETRO	0.067	0.049	0.061	0.048	0.048	0.054	0.092	0.048	0.054	0.056	-	0.009	0.006	-0.006	0.016	-0.014
NIM	0.070	0.053	0.064	0.052	0.052	0.058	0.094	0.052	0.058	0.059	0.062	-	-0.003	-0.016	0.007	-0.024
NRC	0.064	0.045	0.058	0.044	0.044	0.051	0.090	0.044	0.051	0.052	0.056	0.059	-	-0.013	0.010	-0.021
UME	0.091	0.078	0.086	0.078	0.078	0.082	0.110	0.078	0.082	0.082	0.085	0.087	0.082	-	0.023	-0.008
VNIIFTRI	0.064	0.045	0.058	0.044	0.044	0.051	0.090	0.044	0.051	0.052	0.056	0.059	0.052	0.082	-	-0.031
NPLI	0.089	0.077	0.085	0.077	0.077	0.081	0.110	0.077	0.081	0.081	0.083	0.085	0.081	0.103	0.081	-

Table 6 - Inter-laboratory degrees of equivalence at 1 kHz
The upper triangle contains the differences (dB); the lower triangle contains the uncertainties *k* =2 (dB)

1000 Hz	CENAM	DPLA-DFM	GUM	KRISS	LNE	NIST	NMIJ	NPL	PTB	CSIRO	INMETRO	NIM	NRC	UME	VNIIFTRI	NPLI
CENAM	-	0.017	0.030	0.005	0.000	0.017	0.040	0.010	0.010	0.012	0.013	0.024	0.021	0.008	0.027	0.008
DPLA-DFM	0.059	-	0.013	-0.012	-0.017	0.000	0.023	-0.007	-0.007	-0.005	-0.004	0.007	0.004	-0.009	0.010	-0.009
GUM	0.070	0.053	-	-0.025	-0.030	-0.012	0.010	-0.020	-0.020	-0.018	-0.017	-0.006	-0.009	-0.022	-0.003	-0.022
KRISS	0.059	0.038	0.054	-	-0.005	0.013	0.035	0.005	0.005	0.007	0.008	0.019	0.016	0.003	0.022	0.003
LNE	0.060	0.038	0.054	0.040	-	0.017	0.040	0.010	0.010	0.012	0.013	0.024	0.021	0.008	0.027	0.008
NIST	0.064	0.045	0.059	0.046	0.047	-	0.022	-0.008	-0.008	-0.006	-0.004	0.006	0.004	-0.010	0.009	-0.010
NMIJ	0.098	0.087	0.095	0.087	0.088	0.091	-	-0.030	-0.030	-0.028	-0.027	-0.016	-0.019	-0.032	-0.013	-0.032
NPL	0.059	0.038	0.054	0.039	0.040	0.046	0.087	-	0.000	0.002	0.003	0.014	0.011	-0.002	0.017	-0.002
PTB	0.064	0.045	0.059	0.046	0.047	0.052	0.091	0.046	-	0.002	0.003	0.014	0.011	-0.002	0.017	-0.002
CSIRO	0.064	0.045	0.058	0.044	0.045	0.051	0.090	0.044	0.051	-	0.002	0.012	0.010	-0.004	0.015	-0.004
INMETRO	0.067	0.049	0.061	0.048	0.049	0.054	0.092	0.048	0.054	0.056	-	0.011	0.008	-0.005	0.014	-0.005
NIM	0.070	0.053	0.064	0.052	0.053	0.058	0.094	0.052	0.058	0.059	0.062	-	-0.003	-0.016	0.003	-0.016
NRC	0.064	0.045	0.058	0.044	0.045	0.051	0.090	0.044	0.051	0.052	0.056	0.059	-	-0.014	0.005	-0.013
UME	0.091	0.078	0.086	0.078	0.078	0.082	0.110	0.078	0.082	0.082	0.085	0.087	0.082	-	0.019	0.000
VNIIFTRI	0.064	0.045	0.058	0.044	0.045	0.051	0.090	0.044	0.051	0.052	0.056	0.059	0.052	0.082	-	-0.019
NPLI	0.089	0.077	0.085	0.077	0.077	0.081	0.110	0.077	0.081	0.081	0.083	0.085	0.081	0.103	0.081	-

7 Conclusions

The results of the bilateral comparison between DPLA-DFM and NPLI have been analysed using a least-squares technique. The analysis differs from that performed on the CCAUV.A-K3 Key Comparison in the sense that:

+ All the results from the two comparisons are analysed as one large comparison.
+ All results from NPLI are excluded from the calculations of the reference values, while DPLA-DFM serves as link.

The results of the comparison are satisfactory. In cases where the linking laboratories are consistent, as here, the present linking procedure seems to be robust enough to link any two similar comparisons.

8 References

[CCAUV.A-K3] V. Cutanda-Henríquez, and K. Rasmussen, *Final Report on the Key Comparison CCAUV.A-K3*, Centro Nacional de Metrología, México, Danish Primary Laboratory for Acoustics, Denmark, May 2006.

[NIELSEN 2002] L. Nielsen, *Identification and handling of discrepant measurements in key comparisons*, Danish Institute of Fundamental Metrology, DFM-01-R28, 2002.

Appendix – Uncertainty budgets

Uncertainty budgets were requested of the participants in the protocol. They are reproduced here as they were received by the participants.

DPLA-DFM:

Danish Primary Laboratory of Acoustics

Condensed uncertainty budget for type 4160 microphones

The condensed uncertainty budget for a pressure reciprocity calibration of B&K Type 4160 microphones are given in the table below. The background for the budget is given in the following remarks:

Item 1: The figures represents the combined effects of the uncertainty on the coupler length (5 μm) and diameter (5 μm) including the resulting changes in heat conduction corrections.

Item 2: The figures represents the combined effects of the uncertainty on the microphone resonance frequency (200 Hz), loss factor (0.05), cavity depth (10 μm), front cavity (3 mm^3) and equivalent volume (1 mm^3).

Item 3: The figures represents the combined effects of the uncertainty on the measurement impedance, voltage ratios (3 ratios each derived from 4 voltage measurements), cross-talk (< 66 dB) and noise (S/N < 46 dB). It is assumed that cross-talk and noise affects all voltage ratios in the same way.

Item 4: The figures represents the combined effects of the measurement uncertainties on static pressure (40 Pa), temperature (1 K) and relative humidity (5 %).

Item 5: The figures represents the uncertainty on the polarizing voltage (40 mV) and the non-linear relation between polarizing voltage and microphone sensitivity.

Item 6: The figures represents the uncertainty on the applied radial wave-motion correction.

Item 7: The figures represents the estimated error committed by not taking viscosity effects into account.

Item 8: The figures represents the estimated error committed by not taking the increased heat conduction caused by the thread in the microphone front cavity into account.

Item 9: The figures represents the uncertainty on the equations for calculating the speed of sound (0.05 m/s), density of air (10^{-4} $kg/m^{3)}$ and ratio of specific heats (0.0005).

Item 12: The figures represents the uncertainty on applying a correction for dependence of static pressure and temperature on the microphone sensitivity. (Uncertainty on resonance frequency 200 Hz, on low-frequency value of static pressure coefficient 0.0005 dB/kPa and on temperature coefficient 0.002 dB/K, allowed deviation from reference conditions 2 kPa respectively 1 K).

Uncertainty budget for pressure reciprocity calibration of type B&K 4180 microphones

	Components of type B uncertainties in dB*1000												**Frequency Hz**					
	Source	20	25	31.5	63	125	250	500	1000	4000	6300	8000	10000	12500	16000	20000	25000	31500
1	Coupler dimensions	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	3.7	4	5	7	10	15	25
2	Microphone parameters	10	10	10	10	10	10	10	10	10	10	10	12	15	20	30	50	80
3	Electrical transfer impedance	35	25	20	10	7	5	4	4	4	4	4	4	4	4	7	8	10
4	Environmental parameters	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.7	2.1	2.7	3.7	5.6	8.8	15	20	30
5	Polarizing voltage	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
6	Radial wave-motion correction	0	0	0	0	0	0	0	0	0	1	2	3	5	10	15	20	30
7	Viscosity losses	0	0	0	0	0	0	0	0	0	0.2	0.5	1	3	5	10	15	20
8	Equations of environmental parameters	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.3	1.3	1.2
9	Rounding of results	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	$\sigma_B = \left(\sum u^2 / 3\right)^{1/2}$	21.4	16.1	13.5	9.1	8.1	7.6	7.4	7.4	7.4	7.5	7.6	8.8	11.0	15.3	23.3	35.8	55.8
	Components of type A uncertainties in dB*1000																	
10	Allowed reproducibility σ_A	35	25	18	15	12	10	10	10	10	10	10	10	12	15	20	30	50
	Overall uncertainty in dB*10000 at measurement conditions (*k*= 2)																	
	$\sigma = 2\left(\sigma_A^2 + \sigma_B^2\right)^{1/2}$	82.0	59.4	45.0	35.1	29.0	25.1	24.9	24.9	24.9	24.9	25.1	26.6	32.6	42.8	61.4	93.4	149.9
	Uncertainty on corrections to reference environmental conditions in dB*1000 (*k*= 2)																	
11	Correction to reference conditions	3	3	3	3	3	3	3	3	4	5	7	10	15	20	25	35	50
	Overall uncertainty in dB*1000 at reference conditions (*k*= 2)																	
		82.1	59.5	45.1	35.2	29.1	25.3	25.1	25.1	25.2	25.4	26.1	28.4	35.8	47.2	66.3	99.8	158.0
	Resulting uncertainty in dB																	
		0.09	0.06	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.05	0.07	0.1	0.16
	Uncertainty stated in the CMC in dB																	
	CMC values	**0.1**	**0.08**	**0.08**	**0.04**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.03**	**0.04**	**0.05**	**0.08**	**0.14**	**na**

NPLI:

UNCERTAINTY BUDGET FOR MICROPHONE

Quantity and Description	Relative expanded uncertainty (dB)	Probability distribution model	Factor	Sens. Co-efficient	Relative Contribution (dB)
Correlated components					
(U/i) Transfer electrical impedance which include, accuracy of capacitor, resolution of capacitor, Resolution of voltmeter (voltage ratio)	0.05	Normal (2* σ)	½	1	0.025
P_s Ambient Pressure	0.004	Normal	½	1	0.002
$V + V_e$ Volume of coupler, equivalent and front cavity volume	0.04	Normal	½	1	0.02
Polarisation voltage	0.0008	Normal	½	1	0.004
Microphone sensitivity coefficient for temperature and pressure to reference conditions	0.004	Normal	½	1	0.002
ϒ Specific heat ratio	0.004	Normal	½	1	0.002
Uncorrelated components					
(U/i) Transfer electrical impedance	0.003	Rectangular	1/√3	1	0.0017
ϒ Specific heat ratio	0.006	Rectangular	1/√3	1	0.0035
P_s Ambient Pressure	0.002	Rectangular	1/√3	1	0.001
$V + V_e$ coupler volume microphone cavity volume, equivalent volume and microphone constant	0.01	Rectangular	1/√3	1	0.006
ΔH Heat conduction	0.02	Rectangular	1/√3	1	0.01
Polarisation voltage	0.002	Rectangular	1/√3	1	0.001
W Wave motion	0.002	Rectangular	1/√3	1	0.001

Combined relative uncertainty (Coverage factor k = 2)

$$U_{rel,\,95}(M) = \frac{U_{95}(M)}{|M|} = 0.069 \text{ dB} \simeq 0.07 \text{ dB}$$ "